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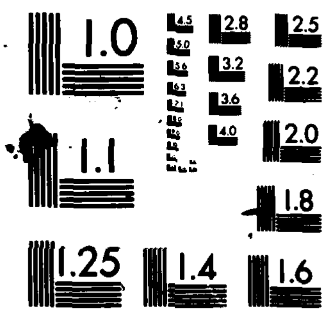

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FINAL REPORT

A PROGRAM TO STUDY THE DETECTION OF TARGET HITS BY DIRECTED ENERGY WEAPONS

Contract F49620-81-C-0045
Report Period: 1 April 1981 - 31 March 1982

Prepared for:

Air Force Office of Scientific Research
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March 1982

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UNCLASSIFIED · 10 JUN REC'D

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR- 82-0571	2. GOVT ACCESSION NO. AD A117 711	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A Program to Study the Detection of Target Hits by Directed Energy Weapons		5. TYPE OF REPORT & PERIOD COVERED Final 1 April 1981 - 31 March 1982
		6. PERFORMING ORG. REPORT NUMBER ASE-4700
7. AUTHOR(s) J.K. Silk		8. CONTRACT OR GRANT NUMBER(s) F49620-81-C-0045
9. PERFORMING ORGANIZATION NAME AND ADDRESS American Science and Engineering, Inc. 37 Broadway Arlington, Massachusetts 02174		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2301/A7
11. CONTROLLING OFFICE NAME AND ADDRESS AFOSR/NP, Building 410 Director of Physical and Geophysical Sciences Bolling AFB, D.C. 20332		12. REPORT DATE March 1982
		13. NUMBER OF PAGES 43
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

X-Rays, Directed Energy Weapons, Hit Detection, X-Ray Production, X-Ray Absorption

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is the final report on a study of the detection, using X-ray emission signatures, of target hits by neutral particle beam directed energy weapons. We find that the energy deposition needed for a detectable signature is a small fraction of that required for lethality. This result causes optimism about the feasibility of X-ray hit detection. Two potential obstacles to detection were considered: The naturally occurring background and absorption by the residual atmosphere. Spectral discrimination can solve the background problem. The

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emitted spectrum contains characteristic X-rays, especially K-lines. For metallic targets, the background is small at the characteristic wavelength. The background contribution can be suppressed by narrowing the bandpass. Absorption by the residual atmosphere is negligible above 200 km altitude, At lower altitudes, attenuation is unimportant for nickel or steel targets, but significant for materials with longer wavelength K-lines. The ranges of beam/detector parameter values over which detection is possible are presented. The next steps should be implementation studies. Large area detectors with spectral discrimination are needed. Collecting optics using synthetic multilayer structures are a promising approach.

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ABSTRACT

This is the final report on a study of the detection, using an x-ray emission signature, of hits on target by neutral particle beam directed energy weapons. The basic conclusion of the study is that a detectable signature is produced by the deposition in a target of an amount of energy which is small compared with that needed for a lethal hit. This result is cause for optimism about the feasibility of x-ray hit detection. Two potential obstacles to successful hit detection were considered in the study. They are the naturally occurring x-ray background and x-ray absorption by the residual atmosphere. The background problem can be countered by using spectral discrimination techniques. The struck target emits characteristic x-rays, most strongly the K-line of the target material. If the target is metallic in composition, e.g., nickel, aluminum or steel, the natural background flux at the wavelength of the signature line is small. The background contribution to the detector output can be made negligible by narrowing the detector bandpass around the line. The effects of x-ray absorption by the residual atmosphere were found to be neglible for targets above 200 km in altitude. For targets at lower altitudes detection is unaffected by attentuation for nickel or steel-containing targets, but problems exist for materials such as aluminum or lucite with longer-wavelength K-lines. Final conclusions on the merits of X-ray hit detection require more information on the detailed characteristics of the weapon beam and the targets than are available at this time. The ranges of beam/target parameter values over which hits can be successfully detected are presented graphically. The next steps of evaluation should be studies of the implementation of the x-ray hit detector. Large effective area detectors with good spectral discrimination are needed. A promising approach is to use collecting optics based on mirrors using synthetic multi-layer structures. We recommend that this approach be examined. The tasks needed to accomplish the necessary study are presented.

1.0 INTRODUCTION

This is the final report on a program to study the detection of target hits by Directed Energy Weapons (DEW). These weapons promise to make valuable contributions to our military capabilities, but the process of bringing them eventually to operational status requires the resolution of a number of problems. Some of these are fundamental problems relating to the generation and propagation of the beam of directed energy. Some relate to effective operational use of the weapon once the most basic problems have been solved. One issue of practical concern is hit detection. Hit detection is important because it minimizes the attack time per target leading to increased effectiveness and efficiency of the weapon.

There are several ways to approach the hit detection problem. The one addressed in this program is to seek a hit event signature in the radiation emitted by the struck target. In particular, we propose to detect the emission in the x-ray portion of the electromagnetic spectrum. The observation of x-ray photons shows that a highly energetic event is taking place, indicating that a hit has been made and that there has been an effective interaction between the weapon beam and the target.

The research field of x-ray astronomy can make valuable contributions to the solution of the hit detection problem for directed energy weapons. There are many similarities between the detection of x-rays from a struck target and from a natural celestial source. A fundamental problem in both types of observation relates to the radiation background of near-earth space. Instrumentation and data processing techniques have been developed to deal with this problem in x-ray astronomy and will have direct application to hit detection by x-rays.

X-ray emission can be used for hit direction outside the earth's atmosphere where absorption along the line of sight is sufficiently low. For exoatmospheric DEW applications, two types of weapon are being considered - neutral particle beams and high power lasers. This study examines the case of a beam of energetic light atoms impinging on the target.

The problem of detecting x-ray emission from the target is by no means a simple one. The characteristic signature must be recognized against a radiation background due to cosmic rays, trapped particles, diffuse x-ray emission, celestial x-ray sources, the sun, and the albedo of the earth's atmosphere. The task, though difficult, is not impossible because, for the particle beam weapon, characteristic x-ray lines of the target material represent an important contribution to the emission. If the target is substantially metallic, for example aluminum, steel, or nickel, then the naturally occurring flux includes only an extremely small contribution from the target signature lines. Limiting the detector's sensitive band to the signature lines will suppress the detected background to a very low effective level.

This study was performed to provide basic information on the feasibility of hit detection by x-rays. The program gathered available information on the x-ray emission from a hit target, identified the characteristic line signature approach, and assessed absorption effects due to the residual atmosphere. With information on operational requirements and constraints, the program analyzed the feasibility of hit detection by x-rays and defined baseline systems performance requirements. It was found that the weapon energy on target which will generate a detectable x-ray signature is substantially less than the weapon energy required for lethality. Consideration was given to methods for implementing the necessary instrumentation. An approach was identified that promises to provide the spectral discrimination and large collecting area needed with a good signal-to-noise ratio. It uses collecting optics employing a recently-developed scheme for reflecting x-rays at nearly normal incidence. We describe a follow-on program to evaluate this approach and carry the development of it forward in the direction needed for DEW applications.

The conclusion, that a detectable x-ray signature will be generated by an amount of beam energy which is a small fraction of the energy required for lethality, is an important one. The total energy for launching beams that can be stored onboard the weapon-bearing spacecraft is

finite. It is essential that it be used conservatively and effectively. If no hit detector is provided, each attack on a target would require launching a lethal dose of beam energy, and waiting for evidence that a kill has been accomplished.

If uncertainties in the weapon aiming system result in target misses, one lethal dose of energy would be lost for each miss. With a hit detector that works with a fraction of a lethal dose, correct aiming can be confirmed with a relatively small expenditure of stored energy. The confirmation of correct aiming allows the release of the full attack dose with confidence that it will not be wasted. If there is no confirmation of a hit, the beam can be redirected before the full attack is initiated. While an attack is in progress, furthermore, the hit detector can continuously verify that correct aiming is being maintained. If relative motion, vibration, or electronic drift, for example, cause the beam to wander off target, then the hit detector will indicate this condition and the attack can be suspended until the target is reacquired. It provides continuous verification that the energy released from storage on the spacecraft is being used effectively, and not wasted. This capability has the effect of relaxing the requirements for both energy storage and aiming accuracy, two challenging technical problems. An effect which may be equally valuable is the saving of attack time. Verification that a hit is being made ensures that time, as well as energy, is not consumed in launching misdirected beams. This is an important consideration for some of the DEW missions being considered, envisioning multiple targets which must be engaged in a short time.

This report presents the technical background for the study and describes the detailed tasks which were performed throughout the contract period, 1 April 1981 through 31 March 1982.

2.0 TECHNICAL BACKGROUND

A successful target hit by a directed weapon may inflict crippling damage without an accompanying explosion or other dramatic external sign. For this reason radar or visible light observations of the object under attack do not suffice. Additional evidence of a hit can be obtained from the radiation emitted by the struck target in response to the incident weapon energy. Such radiation will cover a broad spectral range from x-ray to infrared, and beyond, and observations in more than one spectral region may be necessary. The detection of emission in the x-ray range is particularly important because it provides unique evidence that an event involving substantial energy is taking place. X-rays directly indicate an effective coupling of the beam energy to the target.

The problem of detecting x-rays from a struck target is a difficult one. The target will not be a highly luminous x-ray source. It may be at a substantial distance (as much as 1000 km) from the detector system. Further, in near-earth orbit the naturally occurring radiation background is a potential obstacle to reliable detection of small x-ray fluxes. This obstacle can be overcome, as discussed in the following sections, by spectral discrimination techniques.

The problem of detecting an x-ray hit signature against the radiation environment of space is basically the same as the problem x-ray astronomers have worked with for nearly two decades. Both celestial x-ray sources, and targets struck by directed energy weapons, send weak fluxes of energetic photons to detectors in near-earth orbits. For the two cases there are many differences in the emitting regions - emission mechanisms, luminosity, distance from earth - but at the detector the two problems are closely related. The results of the astronomical experiments provide information on the radiation background against which the hit detector must work. The instrumentation that has been developed for x-ray astronomy includes detectors and methods for discriminating between the sought-for signal and the background. A brief review of the

radiation background and detection instrumentation is presented in Appendix A. Much of that material was included in the proposal for this program (ASE-4538). It is repeated here for completeness.

3.0 PROGRAM STATEMENT OF WORK

The statement of work for the completed program is as follows:

Task 1 AS&E will perform measurements of the x-ray spectrum of emission from selected targets irradiated with beams of energetic charged particles. The measurements will be made at the University of Indiana cyclotron in cooperation with SAI. They will include a minimum of three sets of beam parameters (particle type and energy) and three targets. The beam parameters and targets will be chosen in consultation with Air Force and SAI technical personnel.

Task 2 AS&E will collect and review information on operational requirements and constraints.

Task 3 From the information gathered in tasks 1 and 2, AS&E will determine the optimum energy range for hit detection by x-rays, taking into account the target emission characteristics, operational constraints, naturally occurring radiation background, and x-ray detector system characteristics.

Task 4 AS&E will analyze the feasibility of hit detection by x-rays in the optimum energy range and define baseline systems performance.

Task 5 AS&E will prepare a final report containing the complete results of the study and recommendations for further development.

These tasks have all been completed successfully. Task 1 was modified in consultation with, and at the direction of, the Air Force Program Manager. The modification was necessary because the cyclotron at the University of Indiana was not available and the measurement program involving SAI, which had been proposed and anticipated, did not take place. The work-around procedure used involved a literature search for available data and theoretical calculations. These data were used in lieu of those that were to have been acquired by the measurements at the University of Indiana.

4.0 TECHNICAL DISCUSSION

4.1 X-ray Emission from Target Materials

When a beam of "heavy" (compared to electrons) energetic charged particles passes into and through matter, the primary energy loss mechanisms are ionization and excitation of the target material. Many of the collisions between the projectile particles and target atoms result in inner shell vacancies. Subsequent decay transitions fill the vacancies with the accompanying emission of characteristic x-rays, the K, L, M etc. lines of the target material, or an Auger electron. Of these, the K-line emission is the strongest. This fact has been used extensively at AS&E and elsewhere, to obtain "clean" x-ray characteristic spectra for instrument calibration measurements.

X-ray production is the same for comparable beams of charged and neutral particles. For light "heavy" particles (H, H^2, H^3, He, He^3 ..... Li^6) incident on high-Z targets the projectile K-shell radius is large compared to the interaction region for K-shell excitation of the target atom. The moving atom acts as a bare point charge in the collision process and the excitation is not influenced by projectile bound electrons. The excitation is produced by Coulomb forces.

For slow projectiles, with an atomic number which is not small compared to that of the target atoms, the projectile electron clouds participate in the interaction. The beam acts as a beam of neutral atoms. Exchange forces (arising because of Pauli exclusion principle effects in the overlapping electron distributions) produce ionization. At higher projectile velocities (greater than the velocities of the K-shell electrons) the response time of the bound electrons is long compared to the collision time. The Pauli principle effects do not play an important role, and Coulomb excitation is the dominant mechanism again for high-z projectiles as well as for low-z.

The cross-section for K-shell vacancy production is a function of the projectile energy. There is a maximum in the cross-section when the time for the projectile to traverse the target K-shell is on the order of the time for the target K-shell electron to complete one orbit.

The cross-section for the production of characteristic x-rays is related to the cross-section for inner shell ionization by the fluorescent yield, ω, according to

$$\sigma_X = \omega\sigma_K$$

where σ_X and σ_K are the x-ray and K-shell vacancy production cross sections, respectively. The fluorescent yield is a function of the atomic number of the target, rising substantially with Z (Evans, 1955).

Observations of characteristic x-rays date back to Chadwick's first observations in 1912 (Chadwick, 1912) of their emission from thick targets struck by energetic alpha particles. The first observations of characteristic x-ray production by proton bombardment were made in 1933 (Grethsen and Reusse, 1933). A recent review article has surveyed the field (Gray, 1980).

The basic equation is the Merzbacher-Lewis relation:

$$S(E_1) \left.\frac{dY(E)}{dE}\right|_{E_1} + \frac{\mu\cos\theta}{\cos\phi} Y(E_1) = \frac{n\,\Omega\gamma}{4\pi} \quad \sigma_X (E_1)$$

where S(E) is the stopping power of the target material, Y(E) is the average number of target characteristic x-rays per incident particle, is the absorption coefficient of the target for its own x-rays, θ is the angle between the incident beam propagation direction and the normal to the target, ϕ is the angle between the normal to the target and the line of sight of the detector, n is the target number density, γ and Ω are the detector efficiency and solid angle, $\sigma_X(E)$ is the cross-section for x-ray production, and E_1 is the energy of the projectile particles.

The equation is written for the thick target case (i.e, the target is thicker than the characteristic x-ray optical depth). For a thin target μ is replaced by 1/t where t is the thickness. For the case in which the range of the beam particles is much greater than the characteristic x-ray optical depth the first term on the left hand side can be neglected. For the hit detection application, the detected x-rays are emitted back along the beam path, assuming the detector is mounted near the weapon, so $\theta = \phi$ and the angle dependence drops out. Incorporating all these simplifications leads to

$$Y(E_1) = \frac{n\gamma\Omega}{4\pi\mu} \quad \sigma_X\,(E_1)$$

To proceed with the calculations we need to know σ_X (or σ_K and the fluorescent yield). The original plan for this program called for performing measurements to obtain these data. As discussed in Section 3.0 it was necessary to modify this plan and use data from the literature instead. A literature search was performed with the result given in Appendix B of this report. The appendix is a partial bibliography with brief annotations indicating the contents of the listed articles. It can be seen that there has been considerable work in this area. Much of the data has been taken at beam energies below that envisioned for directed energy weapons. This is, in part, because the cross-section maximma come at lower energies (at a few MeV, compared to a few hundred MeV for DEW applications). There are data, nonetheless, up to energies of 4.88 GeV. Measurements have been made with a variety of projectiles and targets.

Typical data are shown in Figure 4-1. The illustration shows the x-ray production cross-section for protons incident on aluminum. This is, of course, the same as the cross-section for neutral hydrogen incident on aluminum because a heavy particle passing through matter exchanges charge with the surrounding material, blurring the difference between a neutral hydrogen atom and a proton. Moreover, as cited earlier, for light projectiles incident on a high-Z target the x-ray production does not involve electrons orbiting the incident nuclei. Representative

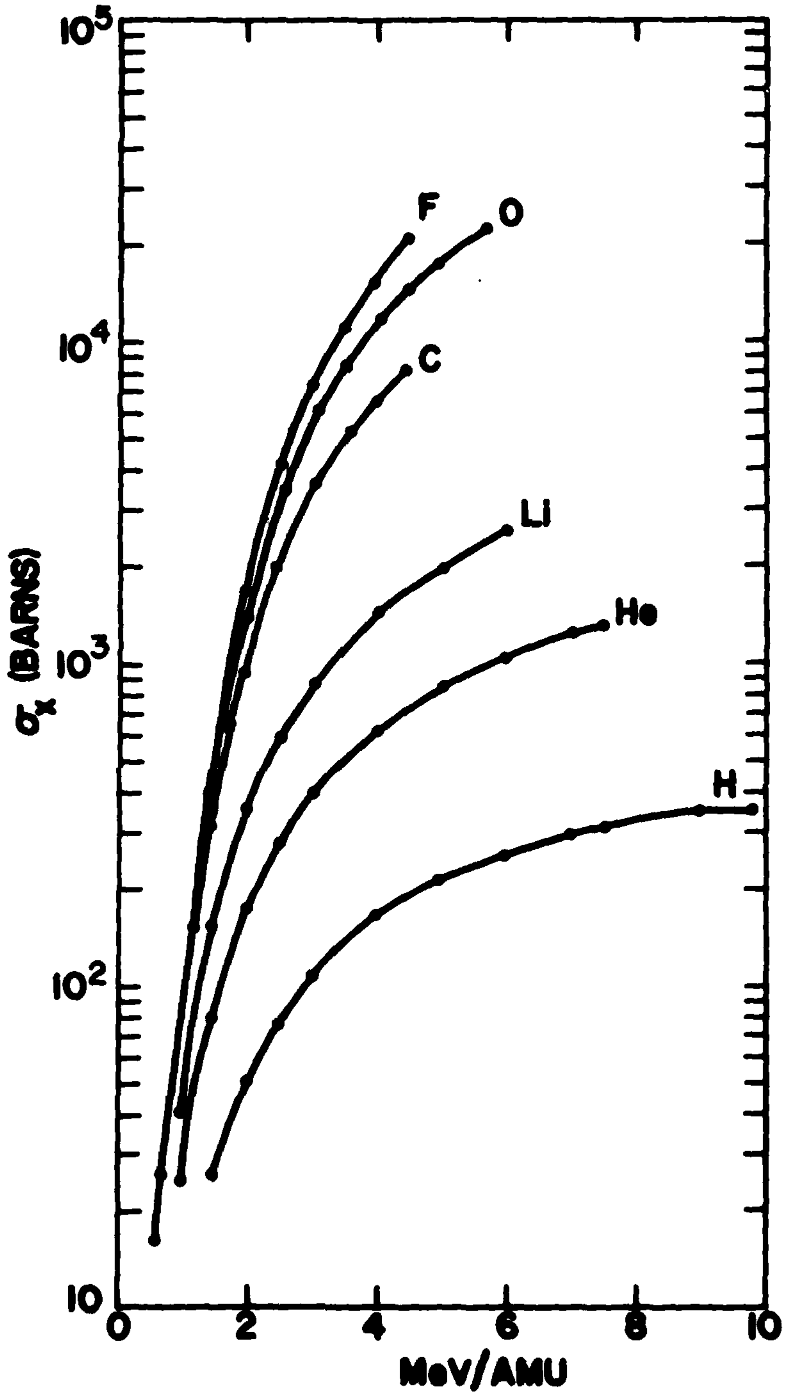

Figure 4-1. Cross section for characteristic K x-ray production as a function of energy, protons on aluminum.

error brackets are shown. They are ± 25% for the Basbas et al. (1973) data, ± 10% for the Basbas et al. (1978) data, and ± 12% for the Sera et al. (1980) data. The three sets of measurements agree, within the experimental uncertainties. For this projectile and target, the maximum cross-section occurs at 3-4 MeV and is large, approximately 1000 barns. At the larger energies appropriate for directed energy weapons, the cross-section is less, but the drop-off is not precipitous. Values of more than 100 barns can be expected in the weapons-energy region.

Further cross-section data for several projectiles are shown in Figure 4-2. Note that the units of the horizontal axis are MeV/AMU so the most energetic particles included in the data are at 92 MeV. The cross section increases approximately as the square of the projectile atomic number, resulting in almost an order of magnitude greater x-ray yield for a lithium beam weapon than for a hydrogen beam weapon. The energy/unit projectile mass, at which the cross-section is maximum, increases approximately with the square of the atomic number of the target. For nickel, the maximum is at approximately 14 MeV/AMU or 84 MeV energy for a lithium beam. The value of the cross-section for x-ray production at maximum is less for the nickel target than for an aluminum one. This is the result of a decrease in the K-shell vacancy production cross-section. The increase in the fluorescent yield does not fully compensate.

Basbas et al. (1973, 1978) have developed a method for combining data from many experiments in a universal curve showing the cross-section as a function of energy. Their formulation is a useful one. It involves plotting the experimental results in terms of dimensionless parameters. They further developed a theory which is in good agrement with the experimental universal curves and which can be used to calculate the cross-section for cases in which experimental data are not available.

4.2 X-ray Propagation in the Residual Atmosphere

As noted in Section 4.1 the x-rays emitted as characteristic lines have rather low energy and are attenuated by modest amounts of material. At

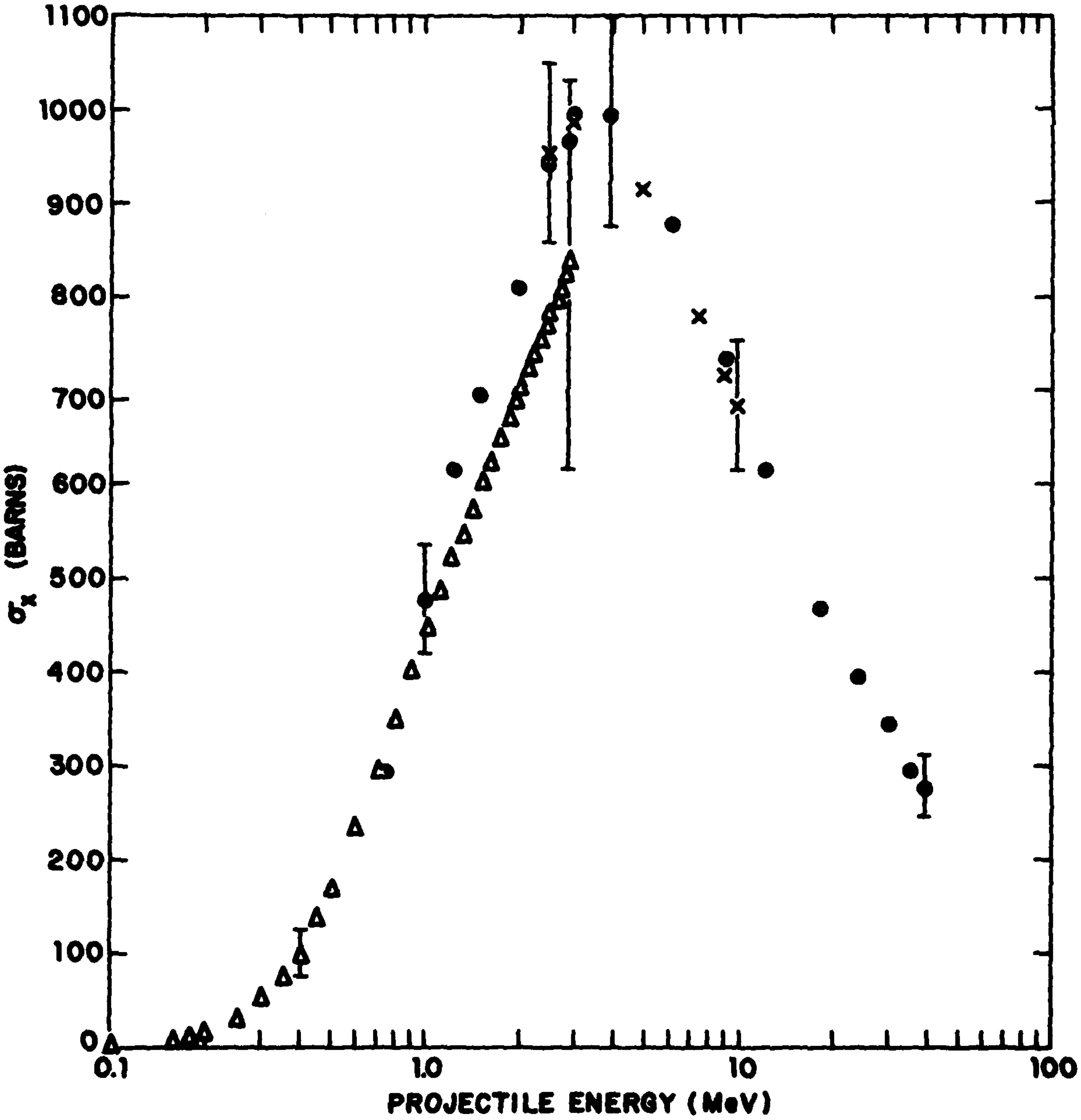

Figure 4-2. Cross section for characteristic K x-ray production as a function of energy, various projectiles on nickel.

altitudes (e.g., 1000 km) the residual atmosphere is sufficiently tenuous that attenuation is not of practical importance, but the absorption of the x-rays emitted by targets at lower altitudes *cannot* be neglected. Atmospheric absorption of the radiation imposes a limit on the lowest altitude at which a struck target can be seen.

Figure 4-3 shows the e-folding length at several x-ray wavelengths as a function of altitude. The wavelengths are those of the characteristic lines of candidate target materials. The calculation was made using data from the U.S. Standard Atmosphere Supplements, 1966 and x-ray data from the McMaster (1969) and Henke and Ebisu (1973). The attenuation can be considered negligible when the e-folding length for absorption is greater than, say, 1000 km. The altitude at which this condition exists depends on the x-ray wavelength. For 2.65 and 1.93 A wavelength x-rays (Ni and Fe targets) the e-folding length is greater than 1000 km down to almost 100 km altitude. For the most heavily absorbed wavelength included in the calculation, oxygen-K at 23.6 A, the e-folding length is less than 1000 km for altitudes below 190 km.

The attenuation mechanism is photoelectric at these energies. At 120 km altitudes the dominant absorber is molecular nitrogen. It is roughly twice as effective in removing photons from an x-ray beam as molecular and atomic oxygen. At 200 km the attenuation by nitrogen and oxygen are approximately equally important. At 500 km, atomic oxygen dominates. It absorbs ten times the amount absorbed by nitrogen. At 750 km the most important absorber is still atomic oxygen, with helium in second place. At 1000 km, the helium absorption is about 25% of the value for oxygen. At low altitude (120 km) there are seasonal variations in the abundances of the atmospheric components. The summer e-folding length may be as little as half the winter value. At high altitudes, seasonal variations are not important, but the e-folding length changes with changes in the exospheric temperature. The exospheric temperature, in turn, has annual and diurnal variations and is further affected by solar activity and geomagnetic activity. The x-ray e-folding length can

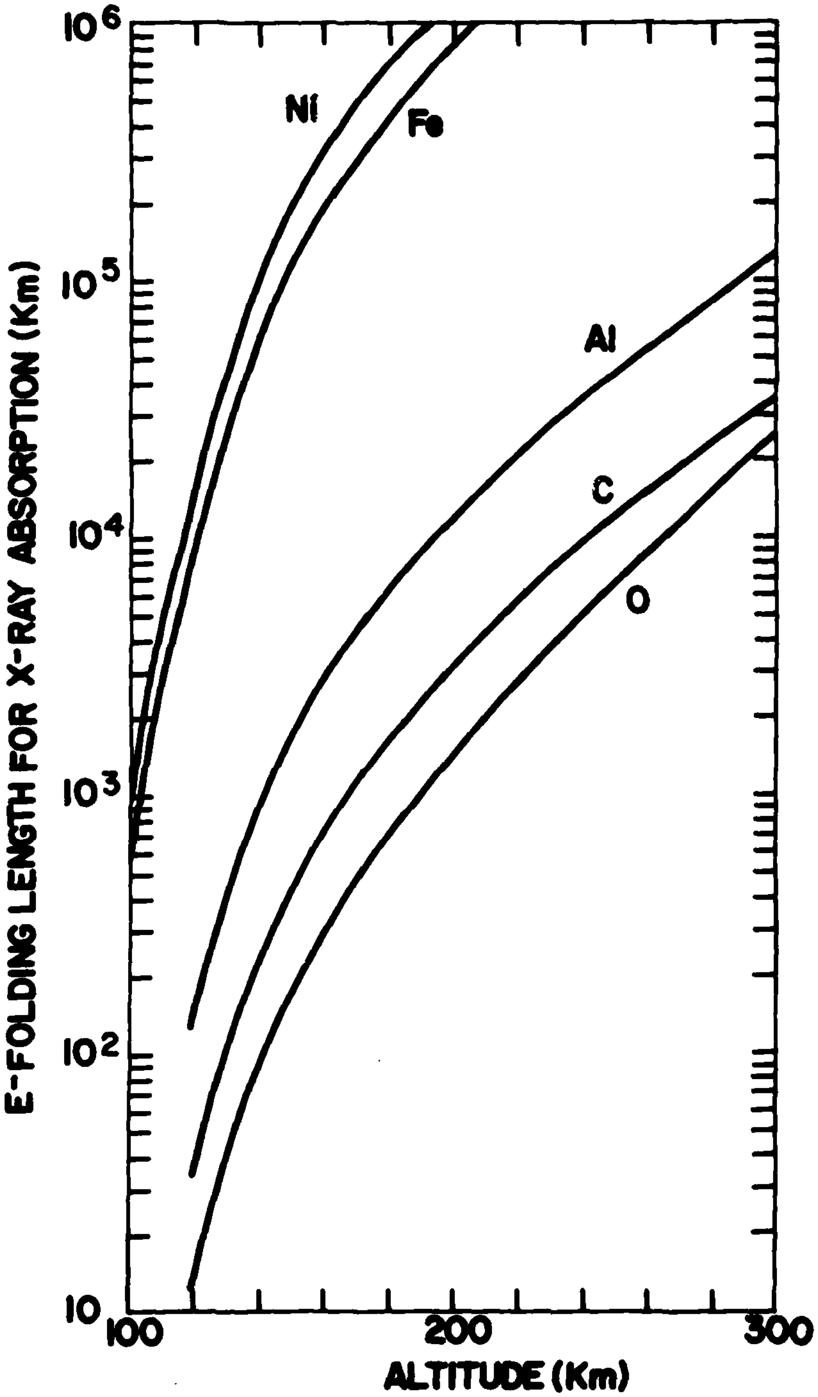

Figure 4-3. The e-folding length for x-ray absorption by the residual atmosphere as a function of altitude for various x-ray wavelengths.

change by orders of magnitude in response to these changes, but the effect is of no practical importance because the minimum values are always much greater than 1000 km.

The conclusion to be drawn from this discussion, and Figure 4-3 is that atmospheric attenuation is of negligible importance if the struck target is at an altitude of approximately 200 km or more. For targets emitting long-wavelength x-rays absorption effects must be considered below that altitude.

4.3 Operational Constraints

The operational constraints for directed energy weapons applications are not well-defined because the work is still in an early phase and many questions are awaiting answers. Among the open questions is the one of what missions will be assigned to the weapon system. Two candidate exoatmospheric missions have been discussed in the open literature. They are an antisatellite mission and one in which the target is a launch vehicle in the boost phase. The two missions have different scenarios and the directed energy weapon has two different roles to play. Considerations such as these and also considerations of technical feasibility dictate that the weapon parameters be treated as variables in the present study.

The performance calculations presented in this report treat ranges of weapon and target characteristics rather than assuming specific values. The question of what ranges to use was addressed in a discussion with the Air Force Program Manager. The result of the discussion is presented in Table 4-1. It is clear that there is a broad range of conditions under consideration. The product of the beam current times the pulse length divided by the square of the distance to the target is a quantity that is closely related to the detected fluxes. It may be as small as 10^{-16} amp-sec/km^2 and as large as 10^{-6} amp-sec/km^2.

TABLE 4-1

PARAMETER VALUE RANGES

Projectile energy	$\geq$ 100 MeV
Beam equivalent current	0.1 to 100 amps
Distance to target	10 to 1000 km
Beam pulse length	1 nsec to 1 sec
Target material	Al, Fe, Ni, U, Lucite

It is to be expected that the strength of the return signal may be large or small, depending on the assumed parameters of the weapon/target system.

One parameter of some significance is not specified in the table. It is the target altitude. As discussed in Section 4.2 attenuation by the residual atmosphere is of no importance at satellite altitudes, but these effects may not be negligible for the boost phase launch vehicle mission. Information on foreign launch vehicle altitude during the boost phase is not readily available in the open literature. It has been stated, though, that the duration of the launch phase is about 8 min. This time is comparable with the boost phase period of NASA's shuttle. In the Columbia 2 Shuttle mission the boost time was 8 min 42 sec. At the end of this period of powered flight the altitude of Columbia was approximately 60 nautical miles or 111 km. The implication, assuming that U.S. and foreign boosters reach similar altitudes in comparable times, is that x-ray detection of hits on a launch vehicle target would require the use of x-rays with wavelength less than 5 A. This is not a serious restriction because the characteristic K lines of all elements with atomic number greater than or equal to sixteen have wavelengths shorter than 5 A. Of the target materials listed in Table 4-1 only aluminum and lucite cannot be observed at low altitudes.

The lethality requirement, i.e., the amount of energy that must be delivered to the target for a successful hit, is an important operational consideration. The specification is not well-defined because of uncer-

tainties about the final weapon design and the target. The question is relevent to this study because the amount of energy delivered to the target is an important parameter in calculations of the x-ray yield. Little information on the topic is available in the open literature. One rough estimate (Bekefi et al., 1980) is that 100 MJ is required for lethality. The fact that this estimate was made by a critic of DEW suggests that the actual requirement may be less. Even if the requirement is substantially less, it appears that multiple pulses of the weapon described in Table 4-1 will be needed. To deliver 1MJ with a 1 amp beam of 500 MeV projectiles and a 1 μsec pulse length requires 2×10^3 pulses, for example. Such a large number of pulses is not necessarily impractical because such a burst would be launched in 4 msec with a 50% duty cycle. The implication for hit detection is that there is no need to detect the interaction of a single pulse with the target. The hit detector can integrate over a number of pulses, so long as that number is much less than that necessary for lethality.

4.4 Results of Calculations

The information presented in the previous sections was used to calculate the performance of an x-ray hit-detector system. A typical result is shown in Figure 4-4 in which It (the product of the weapon-beam equivalent current and the beam pulse duration) is plotted against $\gamma\Omega$ (the product of the detector efficiency and detector solid angle) for the case that 10 x-ray photons are detected in a single beam pulse. The number of photons per pulse was selected somewhat arbitrarily, but it sufficient to obtain good statistics in a small number of pulses. The projectile particles are hydrogen atoms and several targets were included (Al, Fe, Ni, U). For each target three values for the cross-section for x-ray production were assumed, corresponding to different beam energies (10, 100 and 1000 barns). The graph can be read in either of two ways: one can assume values for the beam current and pulse duration and then read off the efficiency-solid angle product needed for a 10 photons/pulse signal. Alternatively one can assume values for the detector efficiency and solid angle and then read off the current times

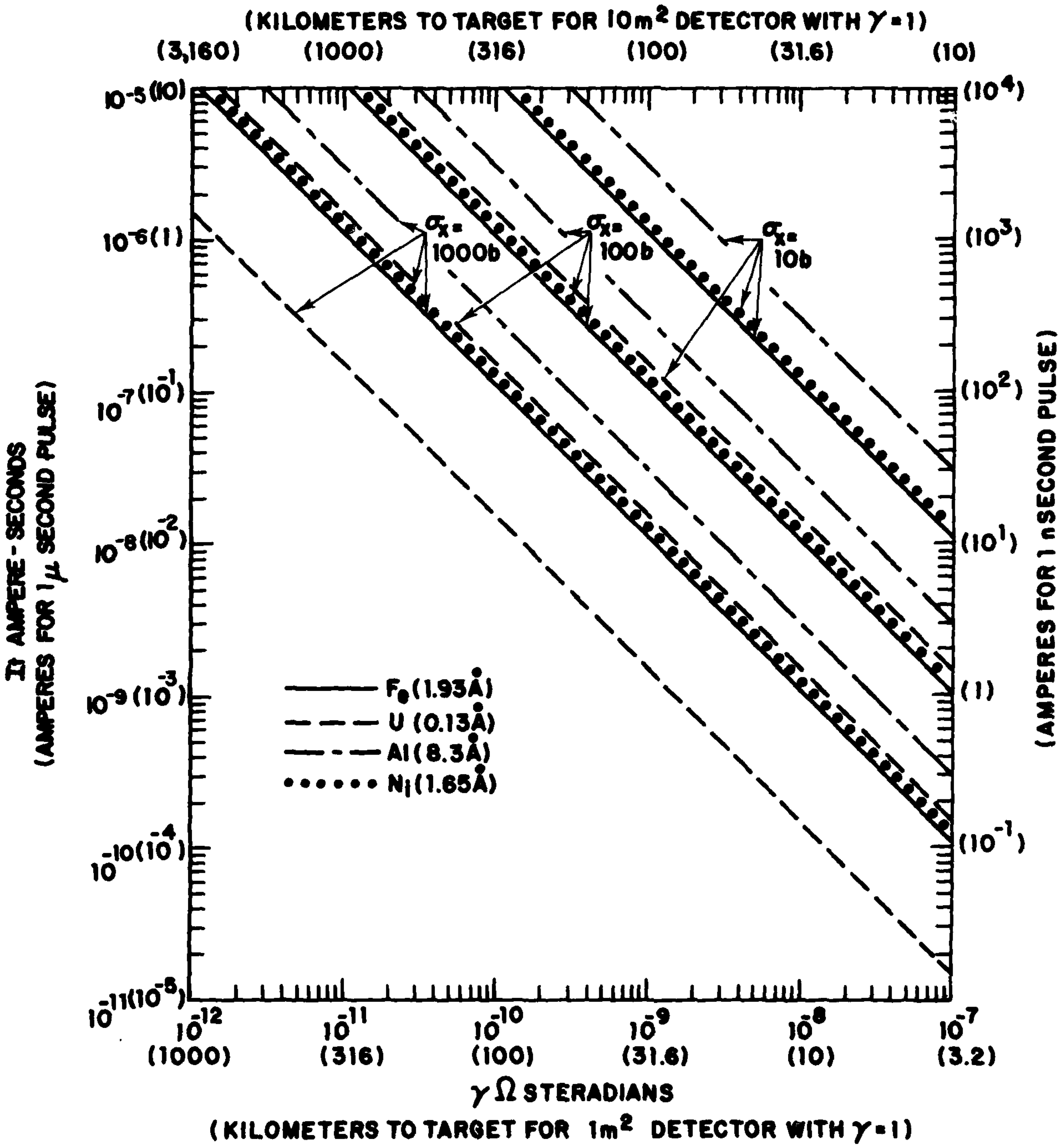

Figure 4-4. Beam/detector parameter limits for a 10 photon per pulse signature. Hydrogen atom projectiles. Various targets and projectile energies.

duration product required for a 10 photons/pulse signal. The curve shows that, for a 100 b cross-section, 10 x-ray photon/pulse are detected when a 1 amp beam of 1 μsec pulses strikes an iron or nickel target at a distance of 100 to 3000 km, depending on the detector area. Ten pulses or less would provide hit detection with good statistics. If thousands of pulses of this beam are needed for lethality, as estimated in Section 4.3, the detection time is extremely satisfactory. The scenario might be as follows: after target acquisition the weapon is aimed and a burst of pulses initiated. If a hit is confirmed during the first ten pulses, the burst is continued to lethality. During this time the hit detector continuously monitors the x-ray flux to verify that the beam continues to strike the target. If the first ten pulses show that no hit has been made, the burst from the weapon is terminated and the aiming corrected. Less than 1% of the lethal energy is expended to verify the hit. The time needed, assuming 1 μsec pulses and 50% duty cycle, is approximately 20 μsec.

For more distant targets, of course, the x-ray signal is less, and for nearer targets, it is greater. Figure 4-5 shows the conditions that produce between 10^{-1} and 10^{3} detected x-ray photons per pulse. The figure shows, for example that if the target is 1000 km away and the weapon is the same 1 amp, 1 μsec device considered above, then 2.5 photons per pulse are detected with a 10 m^2 detector. To collect 100 photons requires 40 pulses, still small compared to the lethality estimate. The cross-section assumed for the figure is 283 b which is the value for iron bombarded by 100 MeV hydrogen atoms.

In the discussion so far it has been assumed that the weapon beam consists of hyrdogen atoms. As noted in Section 4.1, the cross-section for x-ray production increases approximately as the square of the projectile atomic number. The highest Z projectile under consideration for DEW is lithium with a nuclear charge of three. If lithium were used as the weapon beam, the x-ray yield would be greater than that indicated in Figures 4-4 and 4-5 by nearly an order of magnitude. The calculation is shown in Figure 4-6. For lithium projectiles, the one amp, one micro-

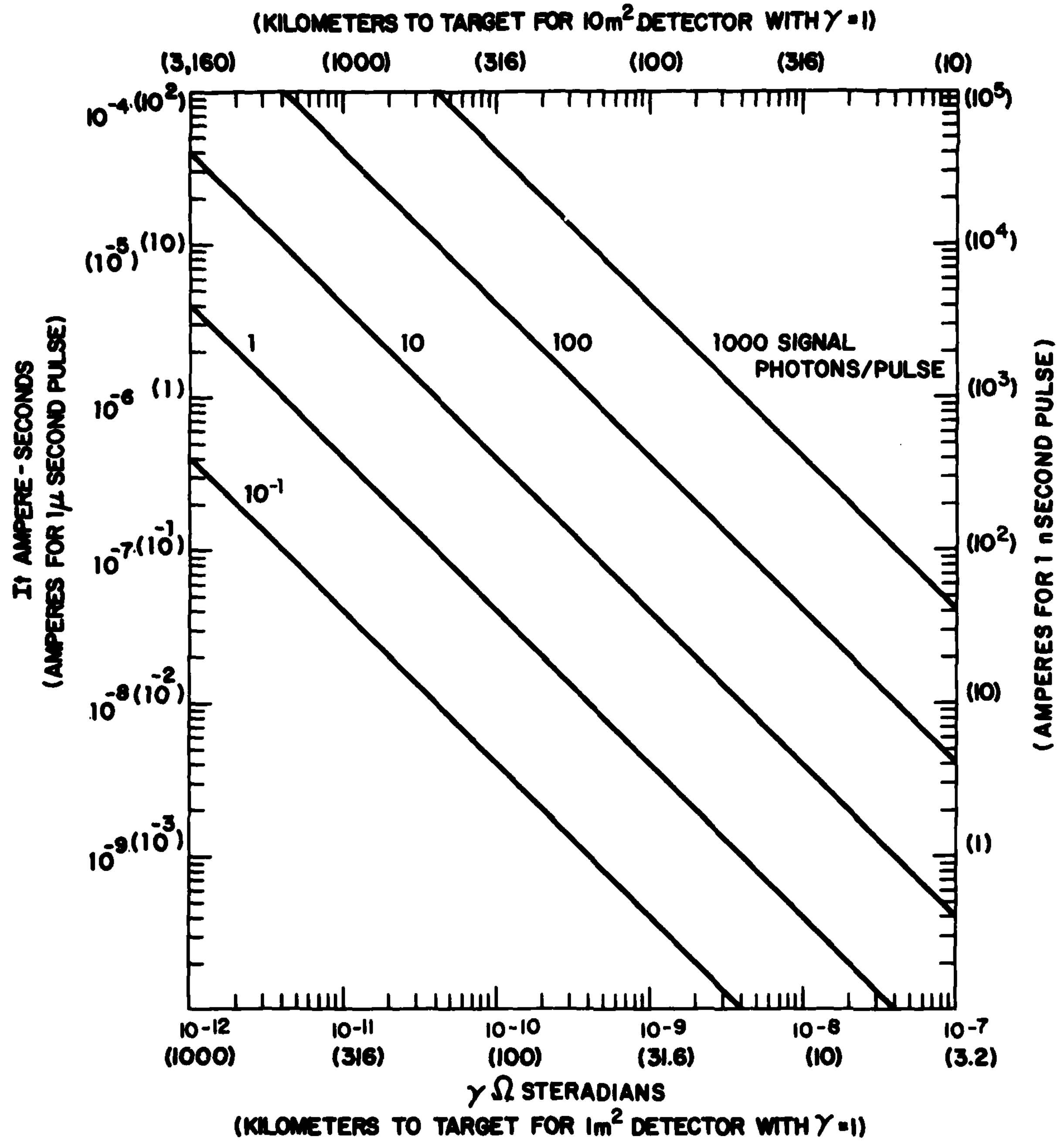

Figure 4-5. Beam/detector parameter limits for various signature magnitudes. The projectiles are 100 MeV hydrogen atoms. The target is iron.

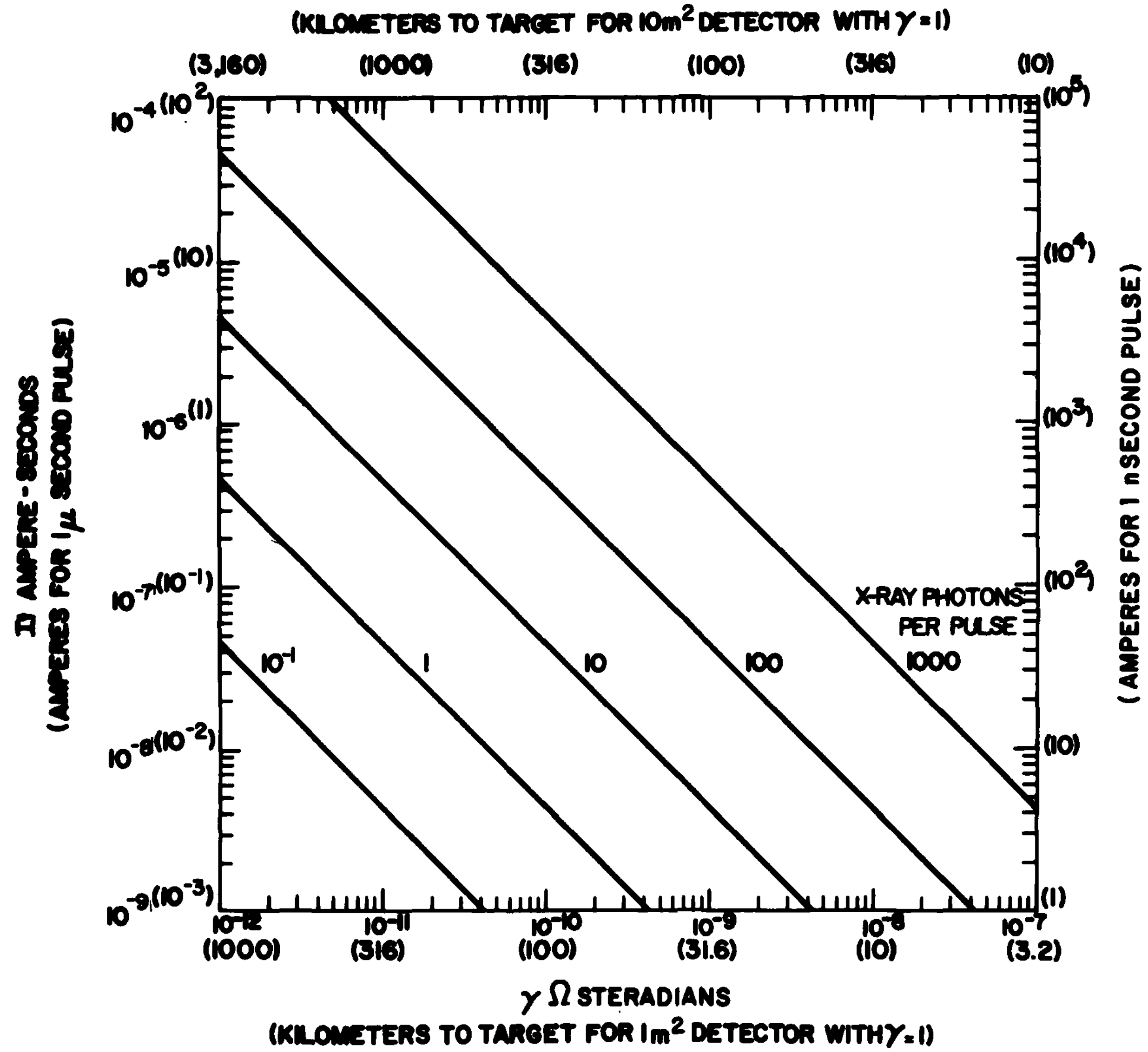

Figure 4-6. Beam/detector parameter limits for various signature magnitudes. The projectiles are 100 MeV/nucleon lithium atoms. The target is iron.

second weapon beam striking a target 1000 km away produces 2.3 - 22 photons per pulse, depending on detector size. The selection of lithium for the projectile facilitates x-ray hit detection considerably.

Lucite is a candidate target material. It is an acrylic resin prepared by polymerizing methylmethacrylate which consists of carbon, hydrogen and oxygen. The fractions by weight are 60% carbon, 8% hydrogen, and 32% oxygen. The K-lines of carbon and oxygen are at 44.54 and 23.57 A, respectively. This means that the detection of hits on launch vehicles in the boost phase should not depend on x-rays from lucite in the target because of atmospheric absorption. For antisatellite missions above 200 km the carbon and oxygen K radiation will propagate essentially unhindered. Background suppression by spectral discrimination is not without problems, however, at least for the oxygen line, which is emitted by the earth's atmosphere, in response to auroral precipitations, for example. These practical considerations argue against basing an x-ray hit detector scheme on the emission from components of the target made of lucite.

4.5 Discussion

The results of the X-ray hit detector performance calculations, presented in Section 4.4, show that, at least for some conditions of potential practical interest, the beam energy required to generate a detectable x-ray signature is substantially less than the beam energy estimated to be required for lethality. This is good reason for optimism about the feasibility of x-ray hit detection. There are residual uncertainties, of course, because the design and mission of the directed energy weapon are not yet well-defined. These uncertainties can only be settled as more detailed information is developed.

An important question which can and should be addressed at this time is the one of hit detector implementation. The performance calculations assumed detectors of 1 to 10 m^2 with an efficiency of 100%. There are

two approaches to implementing such a scheme - large area detectors or focussing optics with large effective area and a smaller detector.

Large area proportional counters and scintillators have been flown in x-ray astronomy payloads (e.g., HEAO-A: 1.54 m^2 total area Xe/CO_2 proportional counters, 0.15-20 keV, in the A-1 experiment and 510 cm^2 total area NaI(Tl) scintillators, 10 - 10,000 keV, in the A-4 experiment). Harshaw Chemical Company routinely produces massive crystals with up to 0.46 m^2 area with uniform scintillation characteristics throughout their entire volume. It can be concluded that a detector of 1 to 10 m^2 area is not unfeasible, and would be accomplished using an array made up of a reasonable number of instruments.

Focussing optics allow the use of a smaller detector, enhancing the signal-to-noise ratio. X-ray astronomy payloads have used grazing-incidence optics (e.g., the Einstein Observatory, 400 cm^2 total area, 0.1 - 6 keV). The use of 1 to 10 m^2 collecting area grazing incidence optics is probably not suitable for the hit detection application for at least three reasons. The first is that such large optics are extr mely expensive. The second is that to reflect x-rays such as the iron and nickel K-lines, very small grazing angles are required, dictating a very large reflecting area to achieve the necessary collecting area, and a very large focal length. The third reason is that grazing-incidence optics are broad-band instruments. For hit detection a narrow spectral response detector is wanted, with the pass band centered on the K-line of the target material.

Recent developments in x-ray optics are leading to imaging systems which make a good match to the hit detector requirements. The new optics operate not at grazing incidence but more nearly at normal incidence, and they have good spectral selectivity. These reflectors are the synthetic multilayer structures. They consist of alternate layers of high-Z and low-Z material. The layer thickness is on the order of a few Angstroms and as many as 200 of them are used in a reflector. They are laid down by either sputtering or evaporation. The synthetic multilayer

structure can be supported on a variety of substrates, including ones thin enough to be bent by applied mechanical forces. The bent surface can be made to approximate an ideal optical figure such as a parabola. Bent glass x-ray optics have been used successfully at AS&E for astronomical rocket payloads and, more recently, for an improved illumination system for x-ray lithography for the VHSIC Program. Thus the pieces of technology needed to make a suitable collector for x-rays from a struck DEW target exist. It remains to put them together properly.

The monochromatic reflectivity is an important benefit for the present application. It allows us to restrict the x-rays reaching the detector to a narrow range of wavelengths, virtually eliminating the background problem discussed in Section 2. The only remaining background contribution is penetrating radiation. The use of optics of provide the collecting area needed means that the detector volume can be made small, reducing the effects of penetrating radiation to a level well below the x-ray signature, at least outside of trapped particle zones such as the South Atlantic Anomaly.

Because the synthetic multilayer structures are used at near-normal incidence the ratio of collecting area to mirror area is nearly as high as theoretically possible. This condition has favorable effects on the cost and the weight of the collector.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The main conclusion from this study is that a detectable x-ray signature is generated when a weapon beam strikes a target and the beam energy required to produce the signature is much less than that required for a successful hit. The signature consists of characteristic x-rays from the target material. The use of this signature obviates problems of background because spectral discrimination can be used to isolate the narrow band return and eliminate background contributions at other wavelenths. The limit on signal detectability is photon statistics.

There are residual questions about the details of the detection scheme. Some of them relate to the exact characteristics of the eventual directed energy weapon and its mission. The beam current and pulse duration determine the number of weapon pulses over which the x-ray return must be integrated for hit detection with good statistics. The atomic weight of the projectile particles is important, with almost an order of magnitude greater return from a lithium beam weapon than from a hydrogen beam weapon. Such question can be answered only as more information on the final form of the weapon and the scenarios for its use become better defined.

There are also residual questions relating to the implementation of the x-ray hit detector. In the energy range of interest either scintillation counters or proportional counters can be used. Both offer limited spectral resolution, and hence spectral discrimination against background. The coupling of a detector to collecting optics, in particular to collecting optics with spectral selectivity, promises an improved signal-to-noise ratio. This approach can be implemented by making use of optics with synthetic multilayer structure reflectors, bent to shape by applied forces. The technology for this approach is in an advanced state of development, but further work is required. This work includes tasks such as an examination of techniques for preparing large area reflectors with consideration given to the bending of large area, initially flat, reflectors and/or mosaic arrays of smaller reflectors. It

also requires analysis to determine the optimum layer arrangement for the x-ray wavelengths involved in x-ray hit detection. An examination of fabrication techniques, and the adaptation of existing methods to large area reflectors is needed. Test peices should be prepared and tested in an x-ray calibration facility. The value of performing these tasks is not dependent on the details of the weapon design and should be carried out in parallel with that effort. The end product would be instrumentation which could be used to support ground tests of weapon beam/target interactions, for example in connection with the Whitehorse Program. We recommend that consideration be given to the funding of a modest effort along these lines.

APPENDIX A

RADIATION BACKGROUND
AND DETECTION INSTRUMENTATION

APPENDIX A

Radiation Background and Detection Instrumentation

A.1 Radiation Background*

The problem of detecting x-rays from a directed energy weapon target or a celestial source is made difficult by the complex radiation environment existing in space. The detector is exposed to spurious photons with energies comparable to the sought-for signal and also to other high energy radiation. Among the background contributions in the same energy range as the signal are secondary radiation produced in the residual atmosphere and spacecraft structures by energetic cosmic rays, the diffuse x-ray background, photons from celestial x-ray sources, and x-rays from the sun or from the sun-illuminated earth atmosphere. The higher energy contributions are penetrating cosmic rays and energetic secondaries, trapped particles, and natural or induced radioactive emissions from the spacecraft and experiment hardware. The radiation environment results in a background counting rate. The background has several effects. It must be taken into account in the interpretation of the measured counting rate, places a limit of the minimum detectable signal flux, and dictates that the detector design must provide for discrimination between the background and the true signal.

The relativistic galactic cosmic ray flux consists mostly of protons, with about 15% helium nuclei, and a few percent heavier nuclei. It is isotropic in near-earth space. The flux is about 1-3 nuclei/cm^2 sec. The spectrum is flat up to about 500 MeV/nucleon and declines rapidly above a few BeV per nucleon. The flux in the lower energy part of the spectrum varies with solar activity.

Energetic cosmic rays produce gamma-rays in interactions with the residual atmosphere and the spacecraft/weapon hardware. The secondary gammas have energies mostly in the range 0.1 to 10 MeV and contribute to

* The radiation background has been reviewed by Peterson, 1975.

the background in several important ways. Some secondary gamma-rays are produced within the detector acceptance aperture, enter the sensitive volume, and are detected like photons from the source under observation. Others eject electrons from detector walls or interact with material within the receiver aperture. It is difficult to distinguish the secondary gamma-rays produced by the cosmic ray flux from true signal photons because the energies and directions of incidence of the two types of particles can be the same. The atmospheric gamma-ray flux has been measured over a wide range of energies, altitudes, and latitudes with directional and omnidirectional detectors. From the empirical data a gamma-ray source model has been developed which is useful for evaluating the flux (Peterson et al., 1973 and Ling, 1975). This model can also be used to estimate an upper bound on the secondaries produced by cosmic ray interaction with the spacecraft, because the spacecraft mass column density is usually less than or on the order of the cosmic ray interaction lengths (Peterson, 1975).

For low equatorial orbits the highest intensities of trapped particle flux are encountered in the region known as the South Atlantic Anomaly, but over much of the near-earth environment the intensities are high enough to prevent low-background observations. Models have been developed which permit the calculation of the instantaneous proton and electron intensity and the integrated dose over an orbit. The electron energy spectrum extends to above 1 MeV and the proton, to above 30 MeV. Some types of detectors must be turned off or otherwise protected during passage through intense trapped particle regions to avoid deleterious effects. In such a case the loss of observing time is typically 20 - 25%. The trapped protons can induce radioactivity in the spacecraft/experiment hardware by secondary neutron capture or spallation resulting in a persistent background increase.

The diffuse cosmic x-ray background extends from a few KeV to 200 MeV with an approximately $E^{-2.1}$ spectrum. The diffuse radiation inside the acceptance aperture of the detector contributes to the background counting rate. The low energy portion of this contribution can be limited by

input collimators which restrict the acceptance solid angle. The portion above 200 keV can penetrate and adds to the gamma-ray background rate.

Galactic and extra galactic x-ray sources are localized in the sky and they will contribute to the detector background only when the line of sight from the detector to the region under observation is pointed at the location of a celestial source. Such a line-up may not be a common occurence, however a celestial source may contribute substantial confusion if it is in the field of view because of time variability.

Among binary galactic x-ray sources Cen X-3 and Her X-1 display periodicities on the scale of seconds (4.8 and 1.24 sec, respectively) and also days (2.067 and 1.7 days, respectively). Cen X-3 also has quasi-random "off" periods of weeks or months duration and Her X-1 has a quasi-regular 11 day on, 24 day off periodicity Cyg X-3, Vela X-1, and SMC X-1 had periods of 4.8 h, 8.95 days and 4.7 days, respectively. Cyg X-1 displays fluctuations as short as 0.5 msec. The luminosities of binary sources are typically 5×10^{37} ergs/sec.

Supernova remnants are less luminous (10^{35} - 10^{36} ergs/sec) and their spectra are generally softer than the binary sources Cas A, SN 1572, Tycho's SN, Cygnus Loop, Pup A and Vela X are examples of supernova remnants. The Crab Nebula has a spectrum that has been studied to above 300 keV. It has a spatial extent of 100 arc sec and exhibits pulsar time variability.

Transient x-ray sources, lasting a few weeks to months have been observed up to two or more times per year. Transient gamma-ray sources occur with a much faster time scale, typically tens of seconds.

There are several hundred galactic sources with luminosities of 10^{37} - 10^{38} ergs/sec including Sco X-1 and Cyg X-2 which were among the earliest celestial x-ray objects studied. Some, such as Cir X-1 have extreme variability over a wide range of time scales.

Extragalactic x-ray sources in general produce less flux in near-earth orbit and their spectra decline more sharply with increasing energy than galactic sources. Extended extragalactic objects include galactic clusters such as Perseus, Coma, and Virgo. The first two have luminosity of about 3×10^{44} ergs/sec. Among the compact extragalactic sources are QSO3C273, the Seyfert galaxies NGC4151 and NGC1275, Cen A and Cyg A. The luminosities of the objects are 10^{41} - 10^{45} erg/sec. NGC4151 has the hardest spectrum (7 - 100 keV observed) with a luminosity of 3×10^{43} erg/sec.

Like the celestial x-ray sources, the sun contributes temporarily varying flux to a detector in near-earth orbit. The x-ray emission originates in the solar corona, a million degree plasma, and hence is primarily in the energy range 0.1 to 10 keV. The spectrum hardens appreciably in solar flares, and the flux increases by as much as several order of magnitude. The characteristic rise and duration times of flares are a few minutes, or less, and an hour or two, or less. Even in quiescent periods the solar flux is large, because the source is close by, in astronomical terms.

The solar x-rays may reach the detector not only directly, but also by scattering and/or fluorescing in the earth's atmosphere. The fluorescence is primarily in the characteristic x-ray lines of oxygen (325 eV) and nitrogen (392 eV). During solar flares, the argon K emission line (2.94 keV) has also been observed. The scattered radiation (Thomson scattering) is at even lower energies than the lines. The albedo is, only relevant to observations on the sunlit side of the earth although precipitation of radiation belt particles can result in night-side x-ray emission from the atmosphere. The low energy of the atmospheric x-ray radiation means that it is an important source of background only for observations of very soft x-rays.

From the brief survey presented in this section it can be seen that x-ray detection of directed energy weapon hits must be carried out in a

difficult environment. The x-ray background covers a broad spectral range from a few hundred eV to hundreds of keV. There are strong background and sources, such as the sun, which would effectively mask the hit signal over part of the sky. There are ubiquitous weak sources of background that limit the minimum detectable hit signature flux. There are time-varying sources that can confuse the temporal discrimination of hits against background. As discussed in the next section, hardware and data processing designs have been developed for x-ray astronomy which can be useful in the attempt to cope with this complex problem.

A.2 Detection Instrumentation

The basic detector system for x-ray astronomy consists of a collector, which selects x-rays arriving from a known region of the sky, and a detector, that records the selected x-ray flux. For soft x-rays (0.2 - 2 keV) the collector may be a simple mechanical collimator or a sophisticated grazing incidence telescope. For more penetrating photons, elaborate collimator schemes are needed, as discussed below. Three types of detector are widely used. They are proportional counters, scintillation counters, and solid state detectors. The detector systems flown on rockets, satellites and baloons for x-ray astronomy are designed to deal successfully with the background radiation described in the previous section. In some cases long integration times or repetitive observations are used to obtain a good signal to noise ratio. For the directed energy weapon hit detection application, time is short. It is necessary to design the detector sensitive area and acceptance solid angle appropriately.

A.2.1 Detectors

Proportional Counters. Various forms of proportional counter have been the principal detectors used in the 0.2 to 10 keV energy range (Giacconi et al. 1968). The counter consists of a gas and electrodes which are arranged so that there is a high electric field gradient near the anode. An x-ray photon that is absorbed in the counter gas usually ionizes an

atom of the gas by ejecting a photoelectron from the tightest bound level allowed by energy conservation. A gas multiplication of the charge by 10^3 to 10^5 is obtained before the electrons are collected by the anode. The charge pulse at the anode is a measure of the photon energy. The spectral resolution primarily depends upon the fluctuations in the number of initial electrons and in the gas multiplication. The efficiency of the counter is determined by the x-ray transmission of the detector entrance window and the absorption of the detector gas. Noble gases such as argon or xenon near atmospheric pressure are commonly used often with the addition of 10% of a quench gas such as CH_4 or CO_2 to absorb UV photons, inhibit secondary electrons from the walls, and collisionally deexcite ions.

Scintillation Counters. In a scintillation counter (used from about 20 keV 10 MeV) energetic electrons are produced in a (usually solid) medium by incident photons and excite bound states of the material by collision. Radiative deexcitation releases optical photons. These are detected with a photomultiplier which puts out an electrical pulse proportional to the initial energy absorbed. The common scintillation materials are alkali-halide crystals (NaI or CsI) and organic crystals, plastics (NE-102 or Pilot B), and liquids. The alkali-halides are usually doped with 10^{-2} - 10^{-3} mole fraction T or Na impurity atoms to produce luminescent levels intermediate between the filled valence band and the ordinarily empty conduction band.

Solid-State Detectors. Solid-state detectors are based on the properties of electrons and holes in semiconducting materials. They have been used over a broad spectral range from 0.2 to 10,000 keV. A solid-state detector consists of a relatively large volume of intrinsic Si or Ge sandwiched between and in electrical contact with thin layers of n-type and p-type material. Incident x-ray photons interact in the intrinsic material and raise electrons from the valence band to the conduction band. The resulting electron-hole pairs diffuse under the applied field and are collected as a charge pulse at the output electrode. Because there are few competing energy-loss or recombination processes in pure

intrinsic material, a large and definite fraction of the energy loss goes into electron-hole production. As a result the energy resolution is very good (.e.g., 0.47% at 10 keV). The materials used in solid-state detectors are p-type Si or Ge into which n-type Li is drifted to produce Ge(Li) devices.

A.2.2 Discrimination Against Background

With the exception of the Einstein Observatory which employs a grazing incidence x-ray telescope to provide excellent spatial resolution, x-ray astronomy has used collimators to select a portion of the sky for observation. To discriminate against penetrating radiation in the space environment shields are used. A collimator limits the field of view and thus reduces background due to diffuse radiation. Similarly, it reduces the probability that more than one source will be found inside the acceptance aperture of the detector at one time.

Grazing incidence optics have been used for arc second spatial resolution in the energy range below about 6 keV. They allow the detector area to be made much smaller than the collecting area, which can help to reduce the background. High resolution x-ray optics require careful fabrication to exacting tolerances. Simple grazing incidence optics with poorer resolution have also been used in the same energy range as "light buckets".

Recent developments have made it possible to consider a new class of x-ray optical systems. These optics, still in developmental stage, use multilayered structures to reflect x-rays at larger-than-grazing angles. The structures consist of alternate layers of materials with high and low x-ray absorption, prepared by either evaporation or sputtering deposition. The layers are thin (order of a few Angstroms) and numerous (as many as 200 layers). The advantages of this approach include a favorable ratio of mirror area to collecting area and wavelength-selective imaging, which arises because, at a given angle of incidence, the reflectivity is high only in a narrow spectral band. The implications of

those characteristics for the hit-detection application are discussed in Section 4 of this report.

When only low energy photons need be dealt with, and angular resolution of arc minutes to degrees is all that is needed, a very simple collimator structure can be used, made with thin walls of light weight material. Honeycomb, soda straw, egg crate and slat arrangements have been used. At energies greater than 20 keV, photon penetration becomes important. Anticoincidence shields can remove virtually all prompt background effects due to passage of cosmic rays through the detector. The residual background due to photons that are transmitted through the rear and side of the collimator must be made less than or equal to the diffuse flux entering the detector aperture by choosing the shielding thickness appropriately. A scheme called the Active Anticoincidence Drilled Collimator meets the requirements for a thick-sectioned collimator of low total mass (Peterson et al., 1967). In this system collimation is provided by drilling aperature holes through a scintillator crystal, e.g., CsI, and vetoing detector counts occurring in coincidence with a count in the collimating crystal. Optimized designs of this type of instrument have been developed to maximize the areal efficiency and response. The optimization depends on the radiation environment and hence on the location at which the detector will be used.

Graded shields are passive protective designs in which two or more layers of different materials are used. The layers are chosen so that valleys in the absorption just below the K-edges are covered by the strong absorption above the K-edge of the adjacent material.

The purpose of the collimator and shield hardware features described above is to reduce the effects of background radiation. Data processing techniques are also used. The simplest is vetoing a detector count that occurs in coincidence with a count from an active shield or collimator. Pulse height discrimination can be used to reject counts due to spurious photons when the detector has spectral sensitivity and the source radiation has a well-defined spectrum. Pulse shape discrimination is an

efficient means of rejecting both gamma-rays and penetrating particles. The basis for the discrimination is pulse rise time which is much greater for radiation with a long path length than it is moderate-energy x-rays. The spectral range in which pulse shape discrimination can be used is limited because of statistical fluctuations in the pulse shape at low energies and by long electron ranges at high energies. In multiwire proportional counters the effects of secondaries from the wall can be eliminated by operating in anticoincidence with the outer anodes. The usefulness of this technique is limited to low energies.

APPENDIX B

LITERATURE SEARCH

APPENDIX B

Literature Search

Recent Review:

1) Tom J. Gray, "Target Ionization and X-ray Production for Ions Incident Upon Solid Targets", in Method of Experimental Physics, Vol. 17, Patrick Richard, ed., Academic Press, New York (1980).

Reviews and Tabulations:

2) J.D. Garcia, R.J. Fortner, and T.M. Kavanagh, Rev. Mod. Phys. 45, 111 (1973).

3) R.L. Kaufman and P. Richard in Methods of Experimental Physics, Vol. 13A, Dudley Williams, ed., Academic Press, New York (1976).

4) P. Richard in Atomic Inner-Shell Processes, Bernd Craseman, ed., Academic Press, New York (1975).

5) C.H. Rutledge and R.L. Watson, At. Data and Nucl. Data Tables 12, 195 (1973).

6) T.K. Hardt and R.L. Watson, At. Data and Nucl. Data Tables 17, 107 (1976).

7) R.K. Gardner and T.J. Gray, At. Data and Nucl. Data Tables 21, 515 (1978).

Binary Encounter Approximation (BEA) Theory:

8) J.H. McGuire and P. Richard, PRA 8, 1374 (1973).

9) J.D. Garcia, PRA 4, 955 (1971).

10) J.D. Garcia et al., PRA 1, 280 (1970).

11) L. Uriens, Proc. Roy. Soc. London 90, 935 (1966).

12) E. Gerjuoy, PR 148, 54 (1966).

Semiclassical Approximation (SCA) Theory:

13) J.M. Hausteen and O.P. Mosebekk, Z. Phys. 234, 281 (1970).

14) J.M. Hausteen and O.P. Mosebekk, Nucl Phys. A 201, 541 (1973).

Plane Wave Born Approximation (PWBA) Theory:

15) D.H. Madison and E. Merzbacher, in Atomic Inner-Shell Processes, Bernd Craseman, ed., Academic Press, New York (1975).

Relativistic Projectiles:

16) O.N. Jarvis and C. Whitehead, PRA 5, 1198 (1972). Protons, 160 MeV.

17) R. Anholt et al., PRA 14, 2103 (1976). Protons, 4.88 GeV, Ni-U Targets.

Results for K and L Excitations Using ION Beams on Solid Targets (Since 1973):

18) E. Koltag et al., Z. Phys. A 278, 299 (1976. Protons, 0.9 - 2.5 MeV, Cr, Cu, In Targets.

19) H. Tawara et al., PRA 9, 1617 (1974). Protons, 1.4 - 4.4 MeV, Zn Target.

20) K. Ishii et al., PRA 10, 774 (1974). Protons, 1.4 - 4.4 MeV, Sn Target.

21) D. Burch, PRA 12, 2225 (1975). Protons, 1 - 18 MeV, C Target.

22) H. Tawara et al., PRA 13, 372 (1976). Protons, 0.75 - 4 MeV, Si, Al Targets.

23) G. Bissinger et al., PRA 14, 1375 (1976). Protons, 0.29 - 16 MeV, C. Targets.

24) G. Bissinger et al., PRA 16, 443 (1977). Protons, 18 - 26 MeV, C Targets.

25) F.K. Chen et al., PRA 15, 2227 (1972). Protons, $^1H_2^+$, $^1H_3^+$, 90 - 150 keV, Al Targets.

26) R.C. Bearse et al., PRA 7, 1269 (19730. Protons, 1 - 3 MeV, Ti, Sb Targets.

27) R.B. Liebart et al., PRA 8, 2336 (1973). Protons, 2.5 - 12 MeV, Nd, Cd Targets.

28) R.D. Lear et al., PRA 8, 2469 (1973). Protons, 0.5 - 2 MeV, Fe, As Targets.

29) M.D. Rashiduzzaman et al., J. Phys. B 9, 455 (1976). Protons, 1 - 3 MeV, Ti, Ay Targets.

30) S.M. Shaforth *et al.*, PRA 7, 556 (1973). Protons, 0.5 - 30 MeV, Au Target.

31) C.E. Bush *et al.*, PRA 7, 1601 (1973). Protons, 0.5 - 14 MeV, Pb Target.

32) A. Langenberg and J. van Eck, J. Phys. B 9, 2421 (1976). Hydrogen ions, 0.015 - 16 MeV, C Target.

33) O.N. Davis and C. Whitehead, PRA 5, 1198 (1972). Protons, 160 MeV, Fe-U Targets.

Tabulation of Fluorescent Yield:

34) C.M. Lederer, J.M. Hollander, J. Pearlman, *Table of Isotopes*, Wiley, New York (1968).

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